SAFETY OF BUILDING CRITICAL INFRASTRUCTURES AND TERRITORIES

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METHOD OF RELIABILITY ASSESSMENT OF ARCTIC PIPELINES IN THE SPACE OF LOADS

Abstract. Arctic pipelines (PL) are located north of the 60th parallel. The main factors that characterize features of such pipelines are the climatic conditions in their areas of installation. Arctic pipeline routes pass through tundra with dwarf vegetation, marshes, and large areas with permafrost lenses, in watery and swampy areas with unique geological and hydrological conditions. The absolute difference of temperatures ranges from –56 degrees Centigrade in winter to 34 Centigrade in summer; and strong winds with speed over 40 m/s. Under these conditions, reliability and safety assessment of pipelines is associated with many principal difficulties, one of which is the need to take into account the simultaneous action (a combination) of many natural and technological loads on the pipeline infrastructure, which are random by nature and can be adequately described only by stochastic processes. Currently, reliability assessment of such systems is not performed due to lack of valid calculation methods.

In this paper a description is given of the first stage of assessing reliability of a pipeline subject to a combination of loads described as random Markov processes. This method, developed by S.A. Timashev in [1], a.k.a. *assessment of reliability in the space of loads*, assumes the ability of constructing admissible areas in this load space with respect to different limit states.

The method is applied to a segment of an above ground arctic oil pipeline with surface corrosion type defects, subjected to a combination (simultaneous action) of four loads: 1) dead weight of the pipe with insulation and oil being pumped, 2) operating pressure, 3) wind load, and 4) exposure to a uniform wall thickness thinning.

The pipeline is considered as a continuous multi-bay thin wall cylindrical beam. The pipeline design is performed according to the (conditional) limit state which is reached when *the equivalent stresses in pipe wall reach the yield stress of pipe material.*

The main purpose of the presented work is reliability assessment of PL in the space of load (impacts). At this the dead load of the pipeline structure is considered to be deterministic. The influence of the wind load, uniform corrosion, and operating pressure (OP) are considered to be variables. For them the permissible region is constructed using the above limit state.

Keywords: pipeline, space of loads, reliability, reliability assessment, surface corrosion, Natural and technological loads.

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МЕТОД ОЦЕНКИ НАДЕЖНОСТИ АРКТИЧЕСКИХ ТРУБОПРОВОДОВ В ПРОСТРАНСТВЕ НАГРУЗОК

Аннотация. Арктические трубопроводы находятся к северу от 60-й параллели. Основными факторами, характеризующими особенности таких трубопроводов, являются климатические условия в местах их прокладки. Арктические трассы трубопроводов проходят через тундру с карликовой растительностью, болота и большие территории с вечной мерзлотой, обводненную и заболоченную местность с уникальными геологическими и гидрологическими условиями.

Разница температур составляет от –56 зимой до +34 °C в летний период; скорость ветра свыше 40 м/с. В таких условиях оценка надежности и безопасности трубопроводов связана с множеством проблем, одной из которых является необходимость учитывать одновременное воздействие на трубопроводы многих природных и технологических нагрузок, которые носят случайный характер и могут быть адекватно описаны только с помощью случайных процессов. В настоящее время оценка надежности таких систем не выполняется из-за отсутствия научно обоснованных методов расчета.

В данной статье описывается первый этап оценки надежности трубопровода при условии описания сочетания нагрузок как случайного процесса Маркова. Этот метод, разработанный С. А. Тимашевым [1], называется методом оценки надежности в пространстве нагрузок и предполагает возможность построения допустимых областей в пространстве нагрузки с учетом различных предельных состояний.

Метод применен к сегменту наземного арктического нефтепровода с коррозией поверхности, подверженному комбинации (одновременному действию) четырех нагрузок: 1) собственный вес трубы с изоляцией и перекачиваемой нефти, 2) рабочее давление, 3) ветровая нагрузка и 4) утоньшение стенки.

Трубопровод рассматривается как непрерывная многосекционная тонкостенная цилиндрическая балка. Проектирование трубопровода осуществляется по предельному состоянию, которое достигается, когда эквивалентные напряжения в стенке трубы достигают предела текучести материала трубы.

Основной целью данной работы является оценка надежности трубопровода в пространстве нагрузок (воздействий). Здесь постоянные нагрузки на трубопровод считаются неизменными. Влияние ветровой нагрузки, равномерной коррозии и рабочее давление считаются переменными. Для них построена допустимая область с учетом описанного выше предельного состояния.

Ключевые слова: трубопровод, пространство нагрузок, надежность, оценка надежности, поверхностная коррозия, природные и технологические нагрузки.

Introduction

Wind pressure in the Arctic zone, due to the fact of climate change is a nonstationary random process. Currently we know too little about it, and does not fit into any of the classic forms of probabilistic description of uncertainty. Therefore, we describe it using a time series of measured wind speeds, using the interval probabilities method [2].

In this paper we estimate the PL reliability through the probability of finding the vector of loads and impacts on a system in the admissible area [1], which is constructed the limit state function [4]. The boundary Γ of this area is found by solving a series of inverse problems at fixed values of the deterministic values and several values of the random variables (RV), which cover the whole area of their existence.

From physics and mechanics of the process it is clear that the maximum allowable wind pressure is at the initial time (start of the system operation) when the whole pipe is brand new. At a fixed corrosion rate for each subsequent moment of time the coordinate *x* of the parabola *y* is the maximum permissible wind pressure on the pipe, i. e., the pressure at which the limit state is realized in at least one of the points of pipeline cross-section. In this case the limit state equations the actual wall thickness as related to the considered moment of time *x*, is used. It is clear that, over time, with the pipe wall thickness thinning, the maximum wind pressure that the pipe can bear will be decreasing.

Now, for each such point (through which the permissible level of wind pressure y) we need to find an interval estimate of the probability that this pressure is exceeded, using interval estimates method, which is based on the Bootstrap method of non-parametric statistics (see below, section 3).

As the final result, we obtain two-sided estimate of the reliability/(probability of failure) of the pipeline. These estimates also are functions of time, form a corridor and have the same shape as the permissible wind pressure.

1. Assessment of the stress state of the above ground pipeline

The general stress state of the oil pipeline is comprised of following components:

- stresses due to the operating pressure;
- stresses, which depend on the oil pipeline temperature;
- stresses, defined by external forces and influences.

The internal OP in the pipe induces circumferential stresses σ_c, which are calculated according formula [3]

$$\sigma_c = \frac{P_{op}\left(D-2wt\right)}{2wt}, \quad (1)$$

where *D* is the pipe outer diameter (OD); *wt* is the pipe wall thickness; P_{op} is operating pressure.

According to [4, 5], the longitudinal axial stresses σ_p in the pipeline due to operating pressure OP and temperature σ_t will be:

In the case when the temperature deformation is compensated

$$\sigma_l^* = \sigma_p = 0.5\sigma_c, \quad (2)$$

In the case when the temperature deformations are not compensated

$$\sigma_l^* = \sigma_p + \sigma_t = \mu\sigma_c - E\alpha\Delta t, \quad (3)$$

where α is the linear expansion coefficient of the metal; *E* is the Young modulus; Δ*t* is the design temperature differential, equal to the difference of temperatures during its layout and when operating; μ is the Poisson coefficient.

The elastic bending of the pipeline in the vertical and horizontal planes induces longitudinal bending stresses, which depend on the influence of different external forces. The bending stresses in the pipeline are calculated using formulas from [4, 5, 6]

$$\sigma_u = \frac{M}{W}, \tag{4}$$

where M is the bending moment; W is the axial resistance moment of the pipe cross section (defined as for a thin wall ring)

$$W = \frac{\pi (D - wt)^2\, wt}{4}, \tag{5}$$

Hence, the overall axial stresses in the pipeline are defined using formula [5, 6]:

$$\sigma_l = \sigma_l^* \pm \sigma_u. \tag{6}$$

The equivalent stresses in the oil pipeline are calculated according to the energy theory of strength [4]:

$$\sigma_e = \sqrt{\sigma_c^2 + \sigma_l^2 - \sigma_c \sigma_l}\ . \tag{7}$$

For any above ground pipeline compression stresses are a hazard, as they may lead to pipeline loss of stability, as well as the extension stresses, which may lead to rupture of the pipe. At this in each cross section of the pipe both types of stresses (compression and extension) may be present simultaneously, as in the considered here case of bending due to the settlement of pipe supports. Hence, when designing a pipeline, four types of stresses should be considered:

- maximal circumferential stress;
- minimal longitudinal stress taking into account its sign;
- maximal longitudinal stress taking into account its sign;
- maximal equivalent stress.

2. Assessment of the longitudinal bending stresses in an above ground pipeline

2.1. Assessment of the bending stresses due to wind load

The linear parts of the above ground oil pipelines on their supports are treated as continuous beams on hinge supports. The design is conducted by taking into account the influence of the transverse dead load/wind load. Calculations also take into account the *vertical displacement of supports*.

Design of a continuous beam with constant cross section on hinge supports section is conducted using the three-moment equation, which for the case of evenly distributed transverse load takes the following form:

$$M_{n-1} L_n + 2M_n (L_n + L_{n+1}) + M_{n+1} L_{n+1} = -0.25q(L_n^3 + L_{n+1}^3), \tag{8}$$

where M_{n-1}, M_n, M_{n+1} are, correspondingly, bending moments on the supports n — 1, n, n + 1; L_n is the span between the supports n — 1 и n; L_{n+1} is the span between the supports n and n + 1; q is the intensity of the transverse evenly distributed load.

If the ends of the pipeline segments are rigidly fixed, then, in order to assess the values of the bending moments at the ends of the pipeline segment, an extra bay of zero length is introduced at the very ends of the segment [6].

The three moments equation is composed and solved for each vertical support of the pipeline segment. When the number of spans is k, we have the system of k — 1 linear equations

$$\begin{cases} 2M_1(L_1 + L_2) + M_2 L_2 = c_1; \\ M_1 L_2 + 2M_2(L_2 + L_3) + M_3 L_3 = c_2; \\ \ldots\ldots, \\ M_{k-2} L_{k-1} + 2M_{k-1}(L_{k-1} + L_k) = c_{k-1}, \end{cases} \tag{10}$$

where $c_i = -0.25q(L_i^3 + L_{i+1}^3)$, $i = 1, 2, .., k-1$, are the coefficients which indicate the right side of equations (8).

It can be proved that

$$M_{k-1} = \frac{\sum_{i=1}^{k-1} c_i a_i}{L_{k-1} a_{k-2} + 2(L_{k-1} + L_k) a_{k-1}}, \tag{11}$$

where

$$a_1 = 1;\ a_2 = -2\left(\frac{L_1}{L_2} + 1\right);\ a_i = -2a_{i-1}\left(\frac{L_{i-1}}{L_i} + 1\right) - a_{i-2}\frac{L_i - 1}{L_i}.$$

After determining the value of M_{k-1}, it is substituted into the last equation of the system (10) the values of M_{k-2} are calculated. Thus, all values of unknown bending moments on the supports are determined sequentially.

According to [4], when the wind load is acting in the horizontal plane, the bending moments are found from equations (10), (11) considering the wind load as being transverse. when both bending moments in the vertical and horizontal planes are present, the design moment should be assessed as follows [4]

$$M = \sqrt{M_v^2 + M_h^2}, \tag{14}$$

where M_v, M_h are the bending moments from the vertical and horizontal loads, correspondingly.

To estimate the limit values of the wind load at a fixed vertical transverse load we define the limit bending stresses. Since the total longitudinal stress (6) has two values (for tension and compression areas), there are two limit states:

$$\begin{aligned} &\sigma_c^2 + (\sigma_l^* + \sigma_u)^2 - \sigma_c(\sigma_l^* + \sigma_u) = [\sigma]^2; \\ &\sigma_c^2 + (\sigma_l^* - \sigma_u)^2 - \sigma_c(\sigma_l^* - \sigma_u) = [\sigma]^2, \end{aligned} \tag{15}$$

where $[\sigma]$ is the yield strength of the pipe material.

From equations (15) we have

$$b_1 = 2\sigma_l^* - \sigma_c;\ c = \sigma_c^2 + \sigma_l^{*2} - \sigma_c\sigma_l^* - [\sigma]^2;\ D_1 = b_1^2 - 4c;$$
$$\sigma_u^{(1,2)} = \frac{-b_1 \pm \sqrt{D_1}}{2};$$
$$b_2 = \sigma_c - 2\sigma_l^*;\ D_2 = b_2^2 - 4c; \quad (16)$$
$$\sigma_u^{(2,3)} = \frac{-b_2 \pm \sqrt{D_2}}{2}.$$

Thus, we have four roots of the two limit state equations, which are pairwise equal to each other bur are opposite in signs. Therefore, from two roots of one limit state (e.g, first one) we need to select the *minimum value of the absolute value*, i.e., the bending stress, which is created by the *minimal ultimate bending moment:*

$$\sigma_{u,\lim} = \min\left\{\left|\sigma_u^{(1)}\right|, \left|\sigma_u^{(2)}\right|\right\};$$
$$M_{\lim} = \sigma_{u,\lim} W. \quad (17)$$

Further, knowing the bending moment from the vertical load, we assess, using formula (14) the ultimate moment from the horizontal transverse (wind) load.

The normative wind load q_w, (N/m) *on* 1 m of PL length should be determined by formula [3]

$$q_w = (q_n^c + q_n^d) D_{in}, \quad (18)$$

where q_n^c is the normative value of the static component of wind load, N/m², determined according to [7]; q_n^d is the normative value of the dynamic component of wind load, N/m², determined according to [7] as well as for buildings with a uniformly distributed mass and constant stiffness; D_{in} is outer pipeline diameter, m, with the insulating cover and the lining.

For simplicity, consider only the static component of wind load. According to [7], the normative value of the static (average) component wind load q_n^c is calculated by formula

$$q_n^c = w_0 k(z_e) c, \quad (19)$$

where w_0 is the normative value of wind pressure; $k(z_e)$ is the coefficient that takes into account the change of wind pressure at height z_e; c is the aerodynamic coefficient.

Normative value w_0 of wind pressure is taken on the Table 1 depending on the wind area [7]. Normative value of wind pressure may be determined in accordance with established procedure on the basis of the Roshydromet meteorological stations data. In this case the w_0 (Pa), should be determined by formula

$$w_0 = 0{,}43 v_{50}^2, \quad (20)$$

where v_{50}^2 is the wind pressure corresponding to the wind speed, m/s, at 10 m above the ground level for terrain type A, which is determined by averaging measurements made in 10-minute intervals and is exceeded once in 50 years.

Table 1

Normative value of wind pressure, depending on the wind region

Wind areas (adopted on map 3 [7])	Ia	I	II	III	IV	V	VI	VII
w_0, kPa	0.17	0.23	0.30	0.38	0.48	0.60	0.73	0.85

Equivalent height $z_e = z_g + d/2$, where d, m, is the pipeline diameter; z_g is the distance from the ground to the pipeline (see Fig. 1).

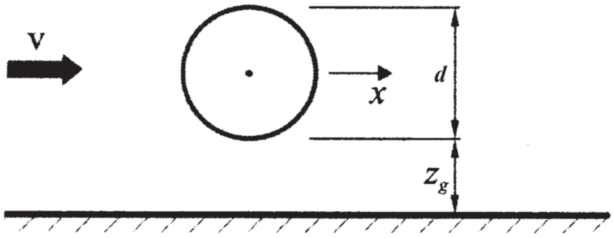

Fig. 1. Scheme of the oil pipeline for wind load

Coefficient $k(z_e)$ is determined by Table 2 or formula (21) [7].

Table 2

Coefficient *k* depending on height

Height z_e, m	Coefficient *k* for terrain types A	B	C
5	0.75	0.5	0.4
10	1.0	0.65	0.4
20	1.25	0.85	0.55
40	1.5	1.1	0.8
60	1.7	1.3	1.0
80	1.85	1.45	1.15
100	2.0	1.6	1.25
150	2.25	1.9	1.55
200	2.45	2.1	1.8
250	2.65	2.3	2.0
300	2.75	2.5	2.2
350	2.75	2.75	2.35
480	2.75	2.75	2.75

In Table 2 [7]:

A stands for open coastal seas, lakes and water reservoirs, countrysides, including buildings with a height of less than 10 m, deserts, steppes, forest steppes, tundra;

B stands for urban areas, forests and other areas, which are uniformly covered with obstacles greater than 10 m in height;

C stands for urban areas with dense buildings higher than 25 m.

The construction is considered to be located in an area of given type, if this area is on the windward side of buildings at distance $30h$ — at the height of buildings h until 60 m and at distance 2 km — at $h > 60$ m.

Note — The types of terrain can be different for different calculated wind directions.

$$k(z_e) = k_{10}\,(z_e/10)^{2\alpha}. \qquad (21)$$

Parameter values k_{10} and α for different types of terrain listed in Table 3 [7].

Table 3

Parameters α and k_{10} depending on types of terrain

Parameter	Types of terrain		
	A	B	C
α	0.15	0.20	0.25
k_{10}	1.0	0.65	0.4

According to [10], the aerodynamic drag coefficient $c = 0.5$.

3. Analysis of wind speed data

Wind speed is usually caused by air moving from high pressure to low pressure, due to changes in temperature. It is of great significance to consider and analyse the static and dynamic effects of high winds on above ground pipelines, because high winds can be very dangerous and destructive. Its loads are randomly applied and dynamic; the velocity of wind varies at various distances from ground, and increases with structural heights. Wind speed is most uncertain and unpredictable when it is closer to the ground. This makes accurate wind load calculations difficult; for reliability analysis of arctic pipelines, an account of the global change of temperatures using wind loads should be taken cognisance of.

Analysis is made considering wind loads as imprecise values for the Svalbard airport stations.

The maxima measured wind speeds over a given period of 25 years from 1990–2014 were taken (Fig. 2), i.e. all together 25 data points.

Bootstrap is a practical nonparametric research method of the distribution of statistics of probability distributions based on multiple generating samples by the Monte Carlo method based on available sampling. It is used, when there is doubt that the usual distributional assumptions and asymptotic results are valid and accurate. This approach allows evaluating the various statistics for complex models: estimated standard errors, confidence intervals, variance, correlation and hypothesis testing (see e.g. Burn statistics). The essence of the method is to construct the empirical distribution on existing sample. Using this distribution as a theoretical probability distribution, a lot of pseudo-samples are generated using a random number generator. After obtaining of the set of pseudo samples the necessary statistical characteristics and their probability distributions are estimated. In order to better understand these wind speed data we mimicked its variability with a bootstrap, as an alternative to the traditional statistical technique of assuming a particular probability distribution. This bootstrap is a procedure of sampling from the empirical distribution of the data, under an assumption that the bootstrapped data are independent and identically distributed.

In our case one bootstrap sample is 25 randomly sampled annual returns. This sampling is with replacement, so some of the years will be in the bootstrap sample multiple times and other years will not appear at all. A thousand bootstrap samples were created. In a nutshell, the steps involve: 1) resampling a given data set a specified number of times; 2) calculating a specific statistic from each sample; and 3) finding the standard deviation of the distribution of that statistic.

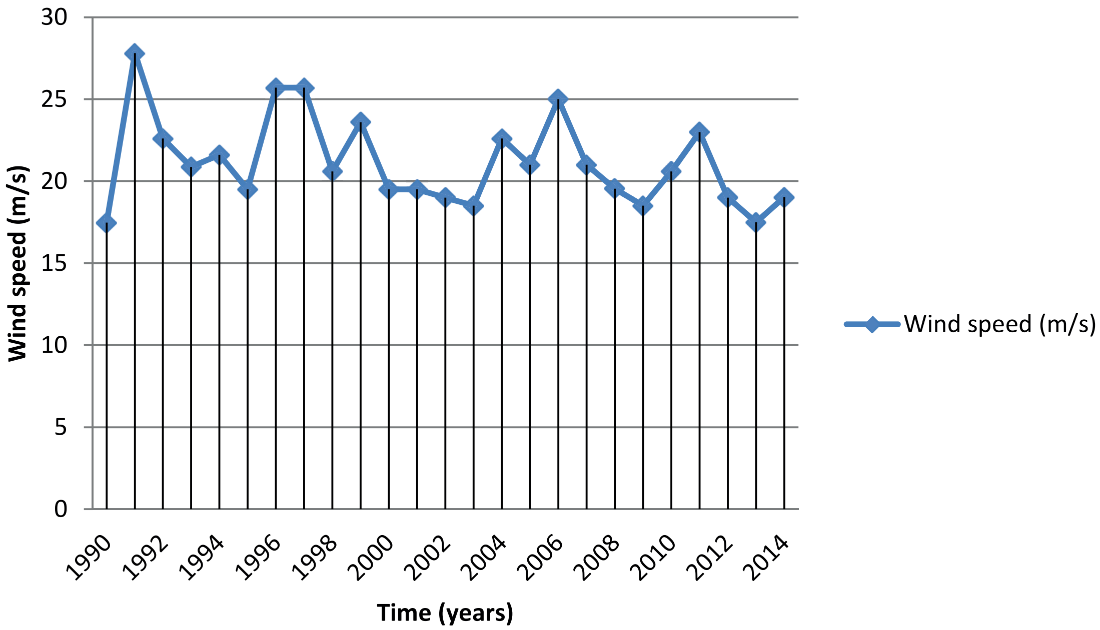

Fig. 2. Maximum measured wind speed over a period of 25 years (Svalbard, 1990–2014)

Intervals of the location and scaling parameters of the type 1 extreme value distribution were created in the script and the maximum and minimum values across all the sample values of the distribution were obtained. A lower and upper probability for the wind speed is obtained by constructing a p-box to characterize uncertainty in wind parameter (Fig. 3 and Table 4) — this is to cater for incertitude and variability.

The p-box is thus constructed:

Suppose $\overline{F}$ and $\underline{F}$ are non-decreasing functions from the real line R into [0, 1] and $\overline{F}$ *(x)* $\leqslant$ $\underline{F}$ *(x)* for all $x \in \mathcal{R}$. Let $[\overline{F}, \underline{F}]$ denote the set of all non-decreasing functions F from the reals into [0, 1] such that $\overline{F}(x) \leqslant F(x) \leqslant \underline{F}(x)$. When the functions $\overline{F}$ and $\underline{F}$ circumscribe an imprecisely known probability distribution, we call $[\overline{F}, \underline{F}]$, specified by the pair of functions, a "probability box" or "p-box" [8] for that distribution.

This means that, if $[\overline{F}, \underline{F}]$ is a p-box for a random variable X whose distribution F is unknown except that it is within the p-box, then $\underline{F}(x)$ is a lower bound on *F(x)* which is the (imprecisely known) probability that the random variable X is smaller than x.

Likewise, $\overline{F}(x)$ is an upper bound on the same probability. From a lower probability measure $\underline{P}$ for a random variable X, one can compute upper and lower bounds on distribution functions using [9]

$$\overline{F}_X(x) = 1 - \underline{P}(X > x) \tag{22}$$

$$\underline{F}_X(x) = \underline{P}(X \le x) \tag{23}$$

Table 4

Wind speed data uncertainty characterization

Wind speed (m/s)	Probabilities		Percentile
	Lower bound	Upper bound	Level
10	1.0000	1.0000	100
11	1.0000	1.0000	100
12	1.0000	1.0000	100
13	1.0000	1.0000	100
14	1.0000	1.0000	100
15	1.0000	1.0000	100
16	0.9563	1.0000	96–100
17	0.8771	1.0000	88–100
18	0.7677	1.0000	77–100
19	0.6381	0.9505	64–95
20	0.4153	0.7911	42–79
21	0.2439	0.5906	24–59
22	0.1355	0.4631	14–46
23	0.0731	0.3515	7–35
24	0.0388	0.2604	4–26
25	0.0204	0.1894	2–19
26	0.0107	0.1361	1–14
27	0.0056	0.0968	0–10
28	0.0027	0.0685	0–7
29	0.0015	0.0482	0–5
30	0.0008	0.0338	0–4
31	0.0004	0.0237	0–2
32	0.0002	0.0165	0–2
33	0.0000	0.0116	0–1
34	0.0000	0.0081	0
35	0.0000	0.0056	0

The summary of the p-box interval estimation in a nutshell is highlighted below:

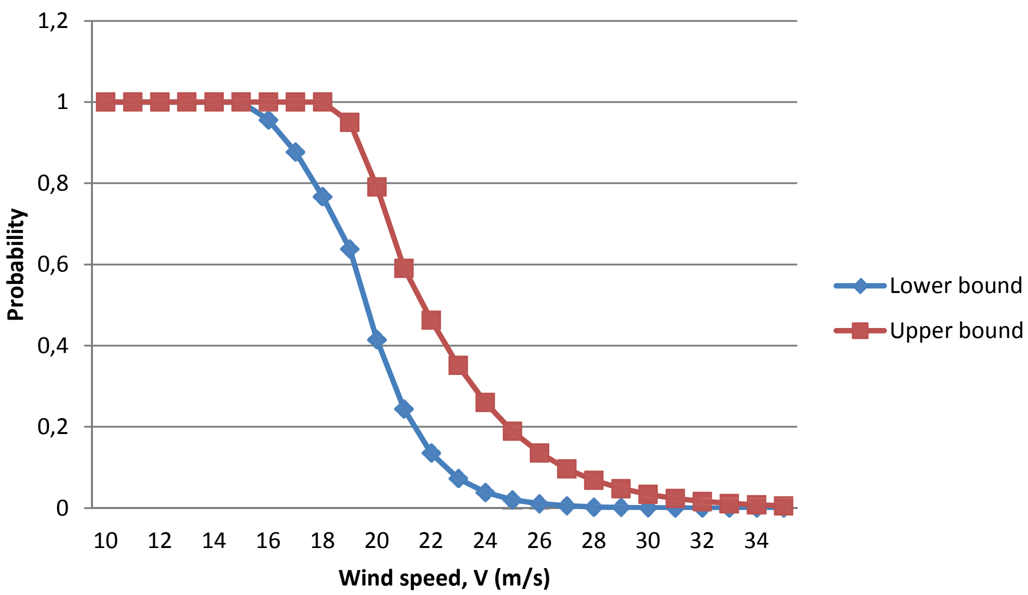

Fig. 3. Probability box for wind speed (Svalbard, 1990–2014)

- get a set of data;
- create a function to evaluate the parameters using maximum likelihood estimates;
- resample from the existing samples using bootstrap;
- give intervals of the location parameters;
- give intervals of the scaling parameters;
- obtain maximum and minimum values across all the sample values of the distribution;
- plot the minimum and maximum values (p-box).

4. Analysis of a real pipeline segment

Consider a segment of a real above ground arctic oil pipeline, parameters of which are given in Table 5.

Table 5

Initial design parameters of an oil pipeline

Transported substance	863,7 kg/m³
Oil density	Above ground
Pipe outlay	863,7 kg/m³
OD	325 mm
Pipe material	steel grade 20, SMYS 245 MPa
Steel density	$7.85 \cdot 10^3$ kg/m³
Pipe wall thickness	9 mm
OP	6.4 MPa
Design temperature	+20 °C
Temperature at pipeline outlay	– 32 °C
Insulation	Epoxy anticorrosion insulation, spiral zink coated folded pipe insulation shell 1,5 mm thick. The insulation proper thickness is 100 mm
Young modulus	$2.06 \cdot 10^5$ MPa
Linear expansion coefficient	$1.2 \cdot 10^{-5}$ 1/°C
Poisson coefficient, a) for elastic performance of metal b) for plastic performance of metal	0.3 0.5

The considered segment has 6 spans which lengths are: $L_1 = 4$ m, $L_2 = 5$ m, $L_3 = 4$ m, $L_4 = 5$ m, $L_5 = 3$ m, $L_6 = 5$ m. For simplicity sake it is assumed that both ends of the oil pipeline segment are rigidly fixed (which creates an error in pipe strength assessment on the safe side). The oil pipeline scheme is given in Fig. 5.

Calculate the linear load. Weight w_p (N/m) of 1 m of pipe length is calculated by formula:

$$w_p = g \cdot \rho \cdot S,$$

where g is the gravity acceleration, m/c²; ρ is the steel density, kg/m²; $S = \dfrac{\pi\left(D^2 - D_{in}^2\right)}{4}$ is the cross-sectional area of the pipe, m².

Then the weight of 1 m of the pipe:

$$w_p = 9.8 \cdot 7850 \cdot 3.14 \cdot \left(0.325^2 - (0.325 - 2 \cdot 0.009)^2\right) / 4 = $$
$$= 686.99 \text{ N/m}.$$

Weight of transported oil w_{oil} (N/m) in 1 m of pipeline is defined by formula

$$w_{oil} = g\rho_{oil}\frac{\pi D_{in}^{\,2}}{4},$$

where ρ_{oil} is oil density, kg/m³.

In our case:

$$w_{oil} = 9.8 \cdot 863.7 \frac{3.14(0.325 - 2 \cdot 0.009)^2}{4} = 626.23 \text{ N/m}.$$

Mass of the pipe hydro/heat insulating shell of 1 m of pipe length is approximately equal to 69.41 kg or 680.22 N/m.

Thus, the total vertical transverse load on the PL is

$$q = 686.99 + 626.23 + 680.22 = 1993.45 \text{ N/m}.$$

The bending moments at which the PL limiting state is achieved, is found depending on the corrosion rate and different values of operating pressure P_{op}. Consider the pipe wall thinning rate is linear and equal to 0.2 mm/yr. Then for each moment of time (corresponding pipe wall thickness) and operating pressure according to formula (17) the ultimate bending moment is calculated. The results are shown in Figs. 5 and 6. Wind loads corresponding to these ultimate bending moments is shown in Figs. 7 and 8.

We calculate the ultimate values for wind speed using formulas (18) and (19). For simplicity, we do not take into account the dynamic component of wind load. Consider section of PL which is 2 m above the ground. Type of terrain is A. The equivalent height $z_e = 2 + 0.350/2 = 2.175$ m. According to formula (21):

$$k(z_e) = 1.0 \cdot (2.175/10)^{2 \cdot 0.15} = 0.633.$$

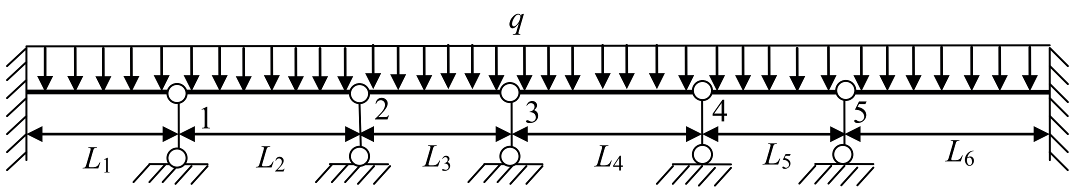

Fig. 4. Design scheme of the oil pipeline segment

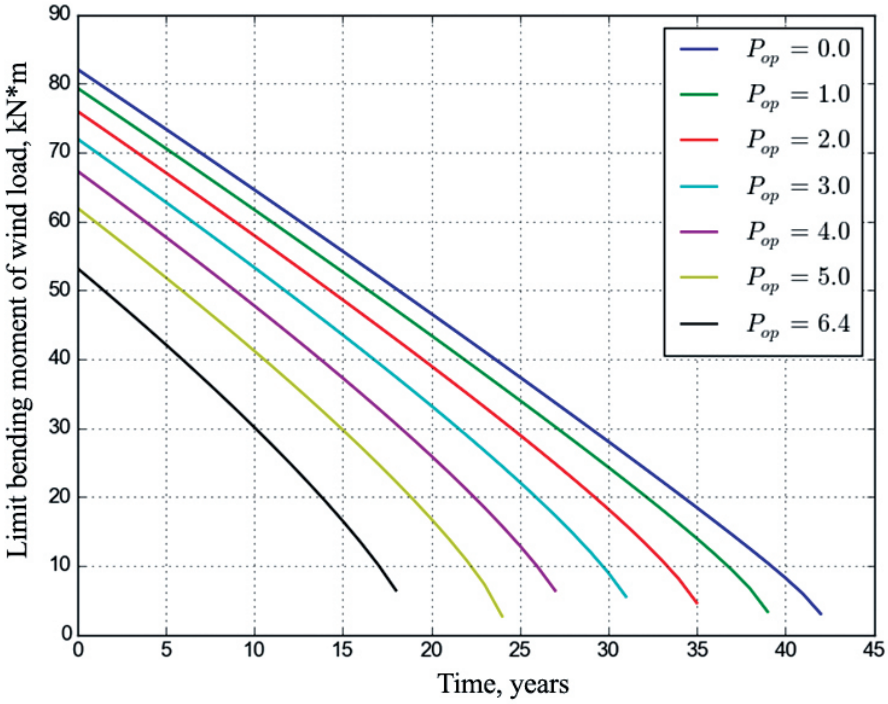

Fig. 5. Ultimate permissible bending moment of horizontal wind load vs time

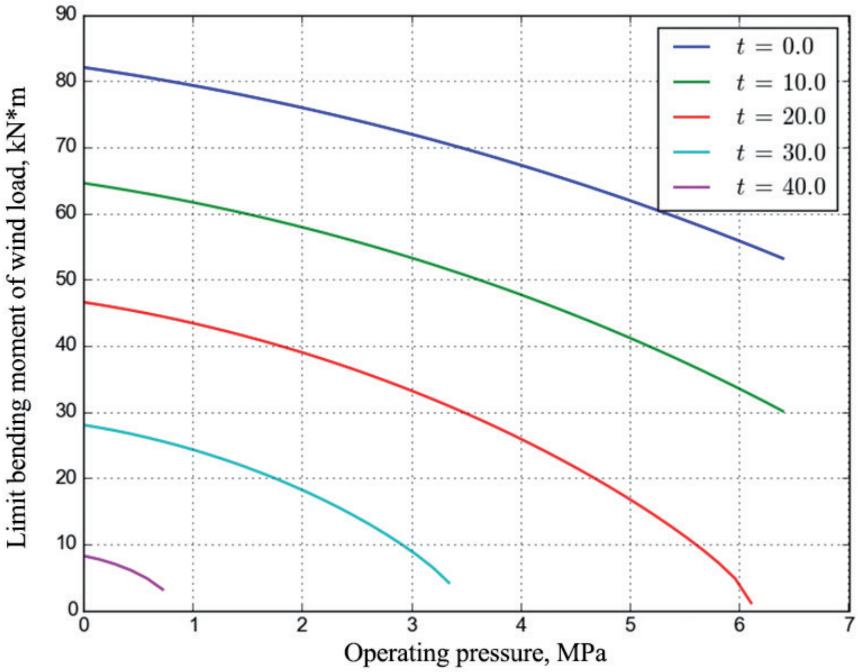

Fig. 6. Ultimate permissible bending moment of horizontal wind pressure vs operating time

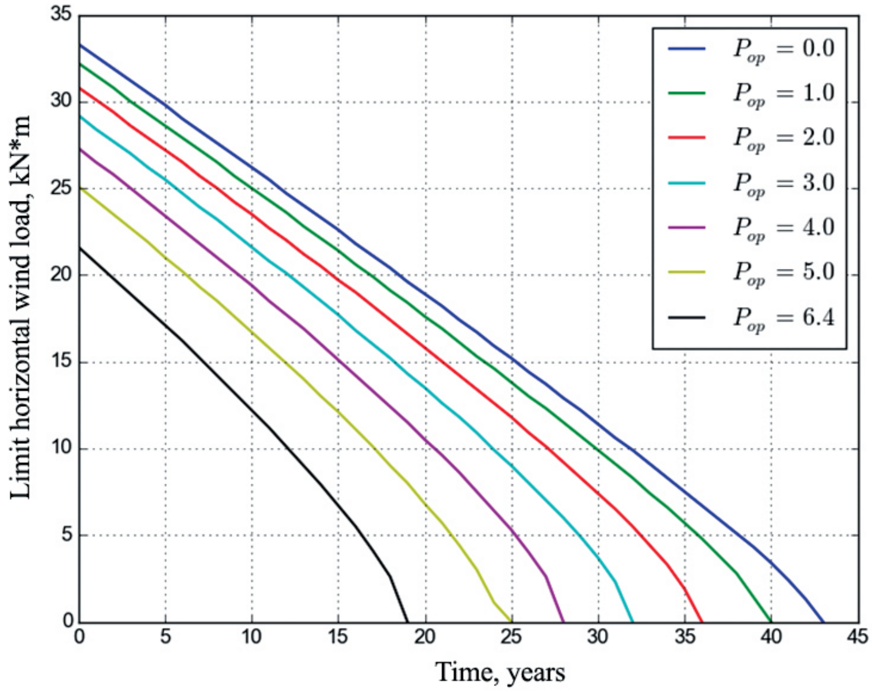

Fig. 7. Ultimate permissible horizontal wind load vs time

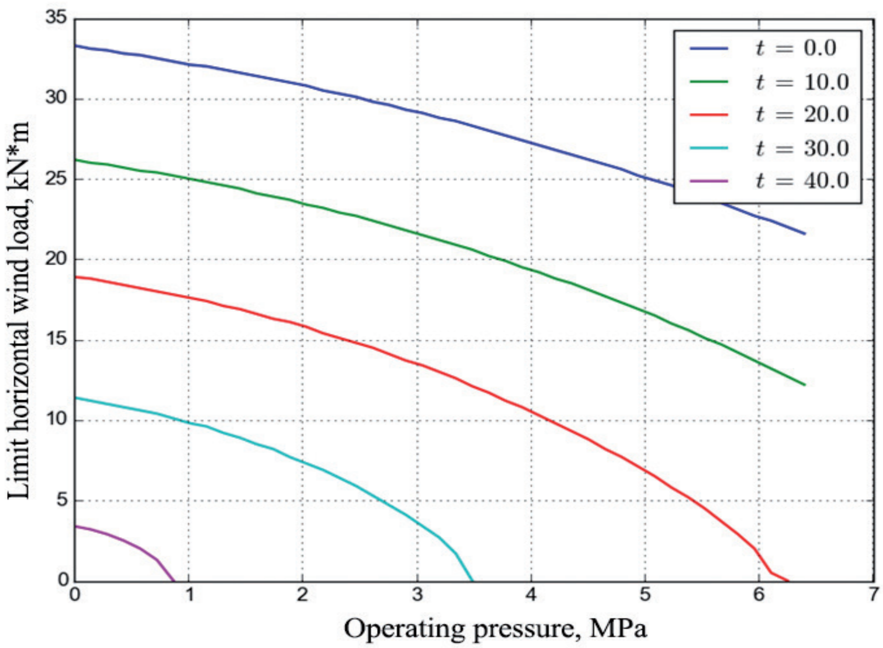

Fig. 8. Ultimate horizontal wind load vs operating pressure

According to [10], aerodynamic coefficient $c = 0.5$.

From formula (18) without taking into account the dynamic component, it follows that

$$q_w = 0.43 v_{50}^2 k(z_e) c D_{in}, \qquad (24)$$

From this formula the wind speed that can occur once in 50 years

$$v_{50} = \sqrt{\frac{q_w}{0.43 k(z_e) c D_{in}}}. \qquad (25)$$

Let time t = 10 years and the operating pressure P_{op} = 5.4 MPa. Substituting q_w into the formula (25) from (24) obtain ultimate limit values of wind load, and the ultimate permissible wind speed values. The results are shown in Figs. 9 and 10.

According to Fig. 10, at t = 10 years and P_{op} = 5.4 MPa, the ultimate wind speed is equal to 18.7 m/sec. According to Table 4 the interval probability of occurrence of such wind speed value is equal to [0.64; 0.95]. Hence, the point wise pipeline reliability in this particular case will be $0.64 \leqslant R_{pl} \leqslant 0.95$. Integrating the whole curve of Fig.10, gives the overall interval of pipeline reliability/(probability of failure).

Conclusion

The advantage of the developed approach is the visibility and ease of interpretation of problem essence. Indeed, even before calculating the reliability function for the engineer it is clear what quality criteria are the most severe, and which elements are not involved in the formation of the admissible region. It allows to select elements with redundant reliability and outline constructive measures to reduce its reliability to the level, which does not affect the overall system reliability.

The specifics of the developed approach is that it splits the task of evaluating the reliability into two independent tasks: 1) constructing admissible areas in load space; 2) assessment the probability of escape of the vector load from the admissible region. In this formulation, the dimension of the problem is not the product of the number of defects on the number of loads in combination, but just the number of loads, which allows to overcome the curse of dimensionality.

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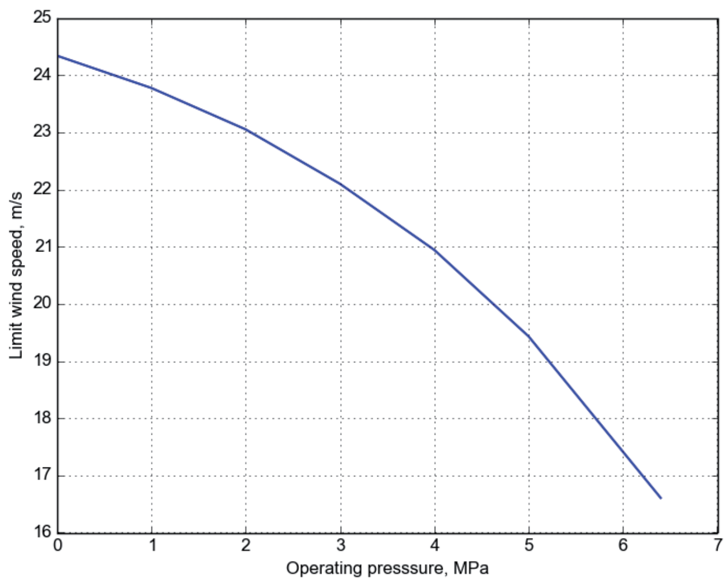

Fig. 9. Ultimate permissible wind speed at time t = 10 years, depending on the operating pressure

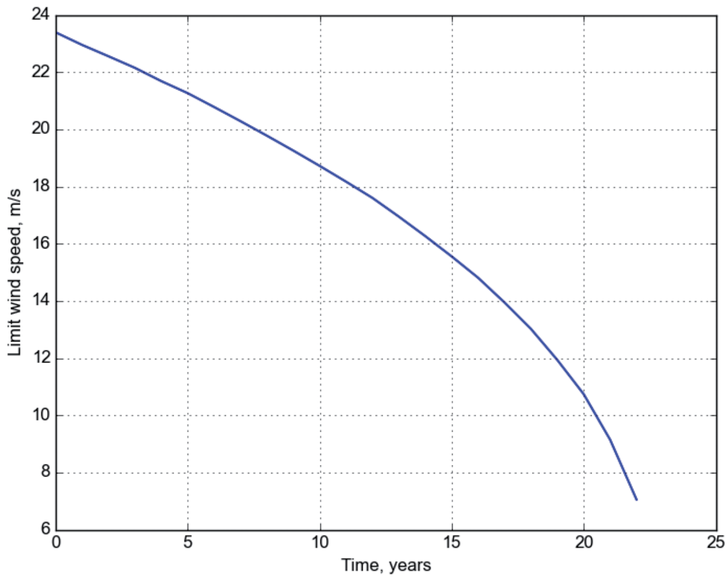

Fig. 10. Ultimate permissible wind speed at operating pressure Pop = 5.4 MPa, depending on the time (corrosion rate)

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